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The free electron laser has the potential of being a highly efficient short wavelength laser. The designs of these lasers are hampered by excessively long optical cavities required by practical considerations of the mirror reflectors. A solution to this problem may be the use of defocussing gas optics in conjunction with the traditional mirror optics. Estimates show that the length of the optical cavity may be reduced by over an order of magnitude with this approach. A program of experimental and theoretical research was carried out to study the various aspects of gas optics for use with the free electron laser.

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GAS OPTICS APPLICABLE TO
FREE ELECTRON LASER TECHNOLOGY

Final Technical Report 1989
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I. Introduction

In order to shorten a FEL cavity more quickly through geometrical divergence, it is necessary to introduce defocusing optics in the near-field of the wiggler. This requires unconventional optics because of the flux densities involved. A solution to this problem is the use of gas optics, which show great tolerance to very high power densities, in place of solid optics near the wiggler. Gas optics can be thought of as weak lenses which can be tailored to the needs of the FEL. The basis of this idea is that under normal conditions, the diffraction angle of the FEL at visible wavelengths is very small being $0(10^{-4})$ radians or less at 0.5μ. This is precisely the range of conditions that can be enhanced with a gas lens.

Gas optics introduce special complications. The first and most important is the construction and design of the gas lens itself. It is necessary to evaluate the Strehl ratio and optical strength of the gas lens because of the high quality beam that is needed for proper FEL operation. Deleterious effects are those associated with turbulence or other nonsteadiness in the lens system and wholesale lens aberrations which can affect the mode structure of the beam and laser operation. Secondly, the operation of the FEL and the e-beam require a high vacuum, while gas optics need pressures comparable to or in excess of one atmosphere. This gas to vacuum interface gives rise to a second set of optical problems and may

affect a ground-based system because of the large vacuum pumping requirements that could be required. The third element brings up the question of non-linear optical effects in the operation of any gas optics element. During the grant period we have concentrated only on the first two problem areas.

II. Summary of Activity

A. Lenses

Our work has concentrated on lens design for three possible lens systems. They are the entry pipe flow gas lens, the subsonic de Laval nozzle lens and the gas mirror. For the convenience of the reader, a short synopsis of the basic operation of each is given in Appendix A. The following is a short report on each of these systems.

1. Entry Pipe Flow Lens

The purpose of the experiment undertaken in 1985 and 1986 was to make quantitative measurements, so that the optical quality of the gas lens could be determined. This entailed considerable extension of the apparatus used in the preliminary experiment. A decision was made to completely rebuild the gas lens: the entrance plenum was enlarged and various diffusers were made for it, the exit plenum was redesigned and rebuilt for more symmetric exit flow from the lens, and the lens tube was replaced due to an obvious lack of straightness in the pipe. The mount for the lens was also redesigned and rebuilt. Fig. 1 shows a schematic description of the latest version of the gas lens assembly.

The method chosen for characterizing the optical quality and optical properties of the gas lens was wavefront curvature measurement by interferometer in the near-field. A Mach-Zehnder interferometer was used for making these measurements because of simplicity of operation. The gas

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lens is required to be vertical in operation to avoid gravitationally induced asymmetry in the flow field, so the interferometer was built in a vertical plane.

In order to measure the shape of the wavefront coming out of the lens, measurements must be made of the fringe pattern of the interferogram. If the lens were perfect, the relative phase of a ray at a given radius from the center of the beam would vary as the square of that radius. Thus, by measuring the phase distribution of the output beam, the focal length (and abberations of the lens) can be deduced. We have semi-automated the procedure with the optical imaging system in the laboratory, and used software to obtain from the fringe pattern the phase distribution of the test wavefront. It is possible to determine from these basic optical measurements the focal length, coma, asphericity, and so on, as functions of Reynolds number, wall temperature, and gas type.

Experiments have confirmed our predictions for an 8 mm ID pipe lens. These experiments have also provided information on the available free aperture of the lens, i.e., the beam diameter of an incident beam which does not strike the pipe wall. Fig. 2 shows a set of example measurements in air for a ΔT of -91°C. Approximately 1/2 to 2/3 of the pipe diameter is useful for defocussing a laser beam.

While these lenses are not aberrationless, nevertheless they perform quite well based on Strehl ratio estimates from the M-Z fringe pattern. The best Strehl ratio (tilt and focus corrected) measurement was about 0.7 at a flow Re_d of about 1000. It is suspected that the Strehl ratio is actually higher due to digitizing error in the computer/CCD camera apparatus, but this had not been proven. While a direct measurement of Strehl ratio may be preferred, the near field data gave us complete information on the

Zernike aberration coefficients of the gas lens. Overall the gas pipe lens worked well and it is conceivable that improvements in optical performance are possible using an axial temperature gradient not possible with this apparatus. A complete description of these experiments can be found in Ref. 1. Further publication of this work can also be found in Refs. 2 and 3.

2. Light Ray Calculations Through an Axisymmetric Nozzle Flow

Flow of a compressible fluid through a nozzle causes the density of the fluid to change. This change of density causes a change in the index of refraction of the fluid. A light ray which passes through the nozzle will encounter the change of refractive index and will change its direction of travel. The flow through an axisymmetric nozzle exhibits the property that the density of the moving fluid is only a function of radius and downstream distance in the nozzle. This density distribution should exhibit some of the same optical characteristics as a lens. Light rays passing through the axisymmetric nozzle flow or gas lens would either converge or diverge. An advantage of the subsonic nozzle flow is that there is no stagnation pressure loss and the power requirement of the flow should be small.

A method was developed to trace the path of a light ray through subsonic flow in an axisymmetric nozzle. Two programs were used to calculate the optical light ray paths. The first one calculated the density distribution in the effects of nozzle flow including the possibility of swirl. The program takes as input a function describing the radius of the nozzle as a function of axial length, a density distribution at the nozzle outlet, and a value for the ratio of specific heats of the gas. The program uses a streamtube method to solve Euler's equations for inviscid compressible flow in an axisymmetric nozzle.[4] The density distribution is output along the

resulting streamlines. This output is used as the input to the second program which computed the optical path length through the nozzle.

The programs described were used to analyze the ray paths through axisymmetric nozzles whose boundaries were described by cosine functions. The nozzles were designed to have a maximum Mach number of approximately 0.8 at the throat. Both converging-diverging and diverging-converging nozzles, as well as different nozzle lengths, were tried. Nozzles whose length was less than three times the radius at the throat caused the density field solution method to fail. For longer nozzles there was no problem in obtaining the solution. A result is shown in Fig. 3 for the distribution of phase, ¢, versus radius. This result was similar for converging-diverging and the diverging-converging nozzles. Nozzles with shorter length had larger ray path angles. This method can be used for flows where the nozzle boundary does change radically. It is possible that the flows in these types of nozzles might produce diverging light ray paths although Fig. 3 shows focussing but the effect seems weak.

3. Gas Mirror

The index of refraction gradient induced by a thermal boundary layer over a heated surface was investigated as a reflecting medium for incident laser light at grazing angles. Due to a non-uniform growth associated with thermal boundary layers, suction through a porous surface was seen as one way to stabilize the thermal layer. This simultaneously induces a velocity to the gas so as to reduce the characteristic time that any gas molecule might be resident within the high power density beam being reflected.

In our experimental setup, a porous surface was oriented on the bottom of a supporting fixture so that the buoyant effects of the heated air would tend to stabilize the boundary layer against the porous surface. The

porous surface was pulled tight across the two lips of the cavity. These lips were machined straight, level and parallel to within 0.0001". No point on the porous surface differed in height more than 0.002" from any other point and there was a strip down the center of the surface that deviated no more than 0.0004". While the surface is by no means "optically flat," it was as flat as could be achieved given the facilities available.

The initial experiment utilized the setup shown in Fig. 4. For many of the early measurements the lateral shearing plate was not used and the far field of the beam was merely photographed 3-5 meters from the gas optics. Besides measuring the conditions of the surface and flow field, the main measurement was of the angle of incidence of the beam shown by the arrows, α. Far field photographs and ray tracing interpretations have shown the effect of a mirror edge on a laser beam. Here the laser beam does not complete its refraction before approaching an edge density gradient resulting in a coma-like appearance to the beam. This effect is confirmed in the ray tracing drawing which shows divergence of beam leaving the heated zone. Figure 5 shows a much more symmetric pattern indicating correct centering of the top hat beam on the mirror assembly. But in this case the refraction was completed too close to the porous surface and its small scale screen regularities affected the airy pattern. Better reflection patterns have been seen with both the gaussian and top hat beam profile.

The assembly gave reflection properties much like a solid mirror would. The angle of incidence of the beam equaled the angle of reflection over a wide range of conditions. The mirror fails at low incidence because the footprint of the beam is larger than the gas mirror assembly and at high angles due to not having enough refracting power available and the light rays strike the porous surface. Larger angles are possible, but require

significantly larger wall temperature. Calculation shows that an α_j of 1.2° is possible at a temperature of 1200°K. These milestones and others are well documented in Ref. 5.

Calculations have shown that the glancing incident trajectory of the laser beam minimizes the distortion caused by surface irregularities in the porous surface. For example, Fig. 6 shows the calculated tilt and focused corrected Strehl ratio vs amplitude of a surface mirror of the gas lens. Here the error is assumed to be a sinusoidal waviness over the porous surface of the form

$$y = A \sin 2\pi \frac{Nx}{L}$$

where A is the amplitude of the roughness in millimeters and N is the number of waves on the surface. The calculations were carried out for an angle of incidence of 1/2°. One finds that small surface roughness results in high Strehl ratio as one expects, but also large values of N or high spatial frequency actually improve the results. Presumably, this is due to averaging caused by the footprint of the beam on the surface. It should be noted that these results were calculated using ray tracing techniques and do not include diffraction effects which could be important at high spatial frequency.

Preliminary experiments utilized the setup shown in Fig. 7. The assembly gave reflection properties much like a solid mirror would. The angle of incidence of the beam equaled the angle of reflection over a wide range of conditions. The mirror failed at low incidence because the footprint of the beam was larger than the gas mirror assembly. At high angles of incidence, the gas mirror does not have enough refracting power available and the light rays strike the porous surface. Larger incidence

angles are possible, but require significantly higher wall temperature. These milestones and others are documented in a paper given to the 7th International GCL Conference.[3]

The most important measure of performance used in testing the gas mirror is the Strehl ratio. The laser and supporting optics were checked for alignment and intensity using a CCD camera. Supporting software on an IBM PC provided the intensity of the laser beam which could be adjusted by a beam attenuator mounted before the pinhole, telescope, spatial filter, and mask assembly. Once the system had reached equilibrium temperature the laser was adjusted to a defined angle of incidence. The laser mounting was then traversed vertically and the state of the beam observed. Precise adjustment permitted almost perfect reflection.

The Strehl ratios, evaluated by the drop in peak intensity of the reflected beam to an unreflected beam, were measured from 85-101%. The average Strehl ratio in the six measurements taken was approximately 95%. The value of 101% was thought to be obtained due to variations in the power output of the laser which was measured on the order of 5-8%. Virtually no tilt or focus has been detected. Thus these early measurements indicate very good Strehl ratios and confirm the ray calculations which predicted the possibility of good optical performance.

To remove potential problems associated with natural convection instabilities of the initial design, a forced convection boundary layer device has been suggested. This newer apparatus attempts to make the flow-field much more robust and stable to disturbances over the previous design. The apparatus has been constructed and underwent preliminary testing. During construction, numerous problems were encountered--most of which were

associated with electrical and thermal isolation of the 1000°K shim from the base optics table.

The design is based on the idea of a laminar boundary layer apparatus to produce high quality reflections. To stabilize the reflection and uniformity of the heated surface, a forced convection boundary layer flow is established over a resistively heated strip of stainless steel shim or mesh. Air flow is provided by a small, low-turbulence wind tunnel (with a measured turbulence level of ≈ 1%) and is accelerated in a duct over the heated surface. The apparatus is shown in Fig. 8. The boundary layer produced inside the wind tunnel is skimmed prior to entry into the duct. Inside the duct the boundary layer growth rate is controlled by the area contraction. This may be altered from the designed constant thickness layer to either a diminishing or growing layer by tilting and/or raising or lowering the duct. Actual measurement of the static pressure gradient inside the duct is possible but to date has not been attempted.

There are numerous factors contributing to the quality of the refracted beam. The most influential of these are the surface temperature, the flatness of the reflecting surface, the steadiness of the flow, and the boundary layer thickness and profile. Surface contact problems with the shim caused wrinkling and use of the mesh was preferred. Suction or high-temperature adhesive may be used to stabilize the shim thermal stresses by creating intimate contact with the support base, but this has not yet been attempted.

Due to the high temperature of the heated mesh, a good indication of the surface temperature is given by the radiation from the surface. Temperatures in the range of 1000-1200°K, which produce an orange glow, are common during a test run. These are close to the limits of the design

operating temperature of 600°C above ambient as proposed; however, reduced cond· .uon losses through the base allow for the higher temperature differential in the actual device. Further, in some test runs the flcw velocity is decreased to allow for a thicker boundary layer and, consequently, lower power requirements.

B. Progress on the Vacuum Interface Experiment

The gas lens operates at atmospheric pressure while an FEL wiggler cavity must be maintained at pressures less than 10^{-8} atm. Clearly some sort of aerowindow device is required at the interface between the wiggler cavity and a gas lens. Any aerowindow suitable for the vacuum interface must have the following two qualities: first, it must act as a high-quality optical element--not significantly degrading the laser beam, and second, it should not permit excessive mass flow from the thermal lens into the wiggler cavity.

Work on the vacuum interface experiment progressed very favorably. Mass flow measurements have been completed for various nozzles, and Strehl ratios have experimentally been shown to be high. In addition, analysis has indicated that the pumping power requirements for cw operation, while large, may be lower than previously expected. The main apparatus consists of a 2.7 m^3 vacuum tank equipped with mechanical pumps and one diffusion pump. On opposing sides of the tank are a laser window and the vacuum interface as shown in Fig. 9. Currently, the interface consists of a simple orifice, however more complicated interface devices (such as aerowindows or swirling flow generators) may be installed. Each orifice is circular with about a 5 mm diameter.

The laser source is a HeNe laser which is spatially filtered, columnated, and masked to a final diameter of between 2.5 mm to 5 mm.

The beam is aligned with the axis of the orifice. With the laser beam aligned, a gate valve (which is external to the orifice) is closed and the tank is evacuated. Upon opening the valve, a free jet flow occurs at the orifice. The laser beam (which is in the near field at the location of the orifice) is then optically perturbed by the flow. The far field pattern is imaged and detected with a digital camera and recorded to computer memory. The recorded information can then be manipulated with software, thereby determining Strehl ratio and focus effects.

The results of the study proved very interesting and, in some cases, surprising. While the measured mass flow rates through the nozzles generally followed theoretical predictions, the optical quality of the aerowindows was surprisingly high. Further, the numerical solution for the optical properties predicted the measured results quite accurately. The numerical work indicated that the aerowindows acted as weakly focusing optical elements with very high focus-corrected Strehl ratios. It also showed that the supersonic portion of the flow field dominated the optical effect. Focal lengths increased with increasing beam to nozzle diameter ratio and decreased with increasing beam diameter at fixed nozzle size. Focus corrected Strehl ratios decreased both with increasing beam to nozzle diameter ratio and beam diameter at fixed nozzle diameter. Focal lengths of 5-20 meters and focus corrected Strehl ratios greater than 0.99 were computed for nozzle sizes and gas properties similar to those used in the laboratory experiment.

The numerical predictions for large focal lengths indicated the aerowindows would act as low Fresnel number lenses, thus a low Fresnel number reference system was used for the laboratory experiment. The intensity distributions measured were found to agree very well with the

theoretical distributions. The experimental results for focal length matched the numerical ones quite well. Focal lengths varied from 9-21 m for nozzle diameters ranging from 3.58-8.33 mm respectively. A sharp-edged orifice produced a focal length shorter than a smooth nozzle with the same diameter. Focal lengths increased slightly with increasing beam size at fixed nozzle diameter.

Focus-corrected Strehl ratios were very high--ranging from 1.0 for the smallest nozzle to .96 for the largest nozzle. These are shown in Fig. 10. While no focus-corrected Strehl ratio dependence on beam size was observed, the Strehl ratio was slightly higher for the sharp-edged orifice than for the smooth nozzle with the same diameter. The numerical work was repeated using a monotomic gas such as argon or helium. It is believed that a solid body velocity component would act to defocus the laser if present. The flow fields were solved numerically and the Zernike aberration coefficients determined. The most complete description of this work is given in Ref. 6 and excerpts were presented at the 7th International Symposium on Gas Flow and Chemical Lasers in 1988.[3]

REFERENCES

1. A.J. Westphal, "Analysis of a Diverging Thermal Gradient Gas Lens," Master of Science Thesis, University of Washington, 1986.
2. W.H. Christiansen, "A Preliminary Study of Defocussing Gas Optics," AIAA preprint 85-1632, 1985.
3. W.H. Christiansen, "Gas Optics Applicable to the Free Electron Laser," 7th International Symposium on Gas Flow and Chemical Lasers, Vienna, Austria, 1988.
4. This program was developed and made available by Prof. C.E. Pearson of the Department of Aeronautics and Astronautics, *J. Computational Physics*, **42**, 257 (1981).
5. S.P. Lawlor, "The Gas Mirror and Its Performances as a Glancing Refractor," Master of Science Thesis, University of Washington, 1986.
6. P.A. Meyer, "The Axisymmetric Free-Jet as an Aero-Window," Master of Science Thesis, University of Washington, 1988.

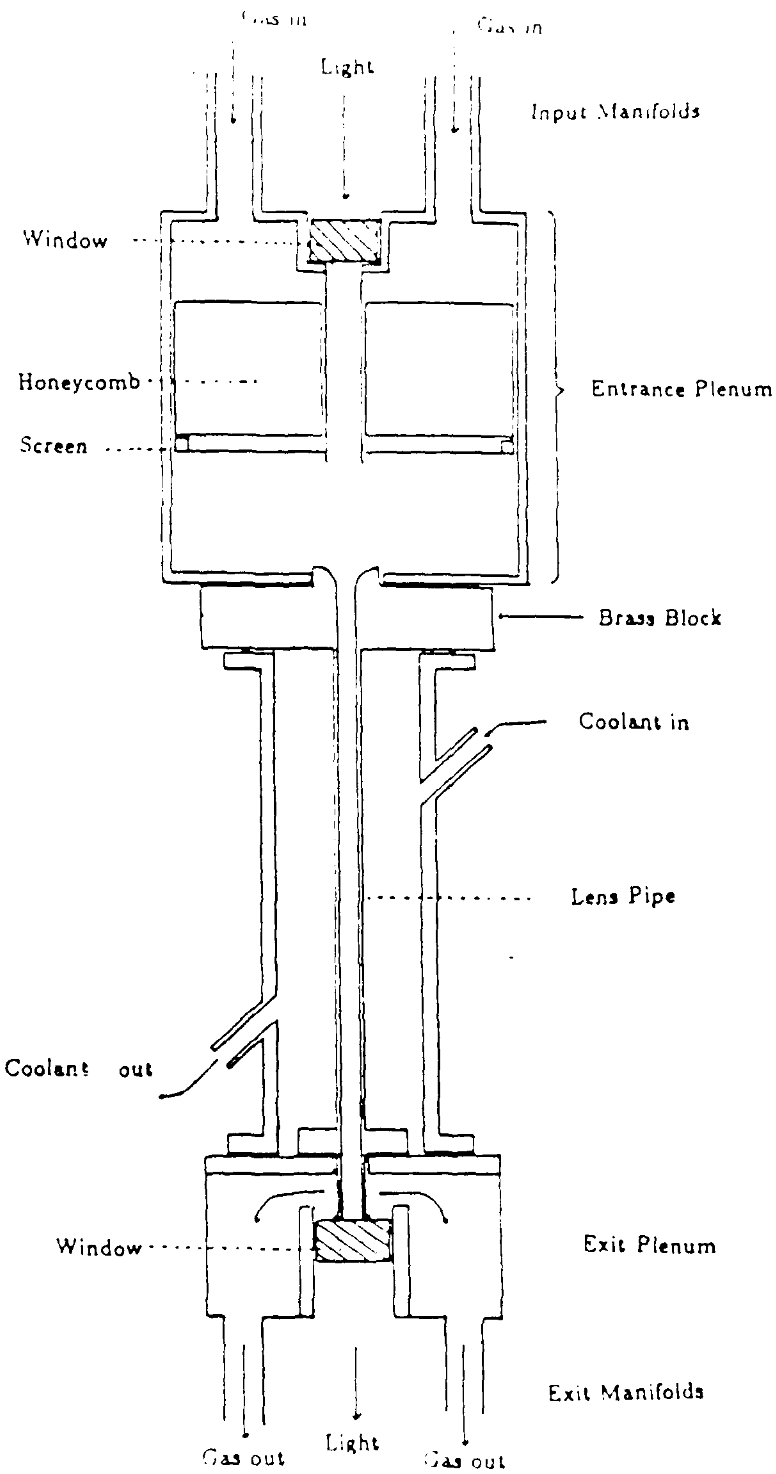


Fig. 1. The Laboratory Gas Lens.

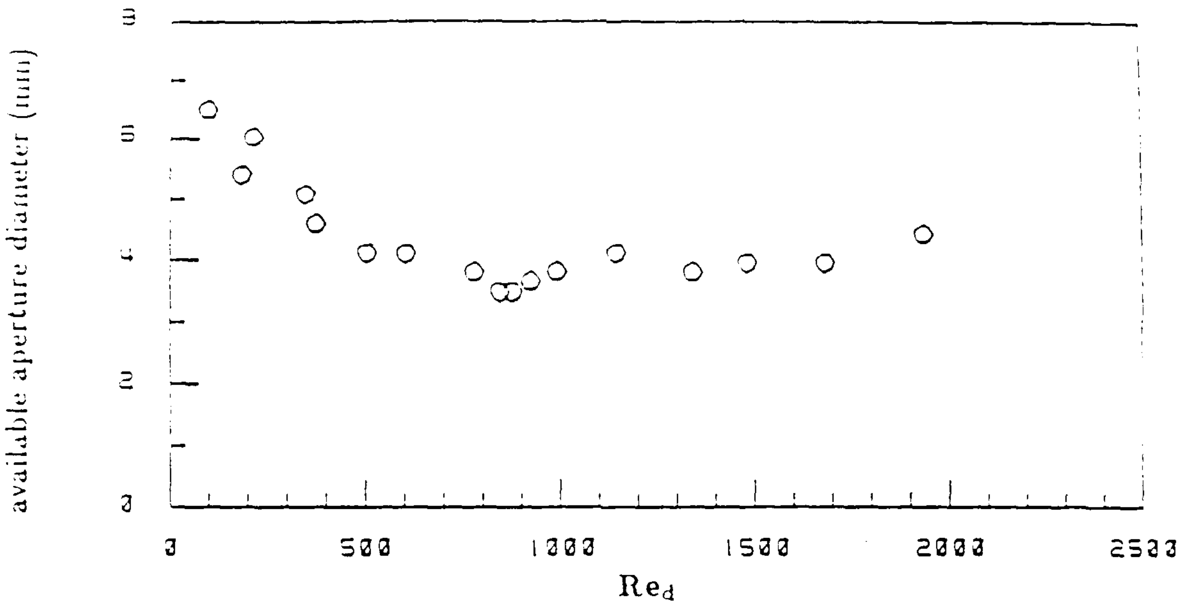


Fig. 2. Free Aperture Measurements for the Gas Lens Running in the Forward Direction for ΔT_0 = -91.0°C.

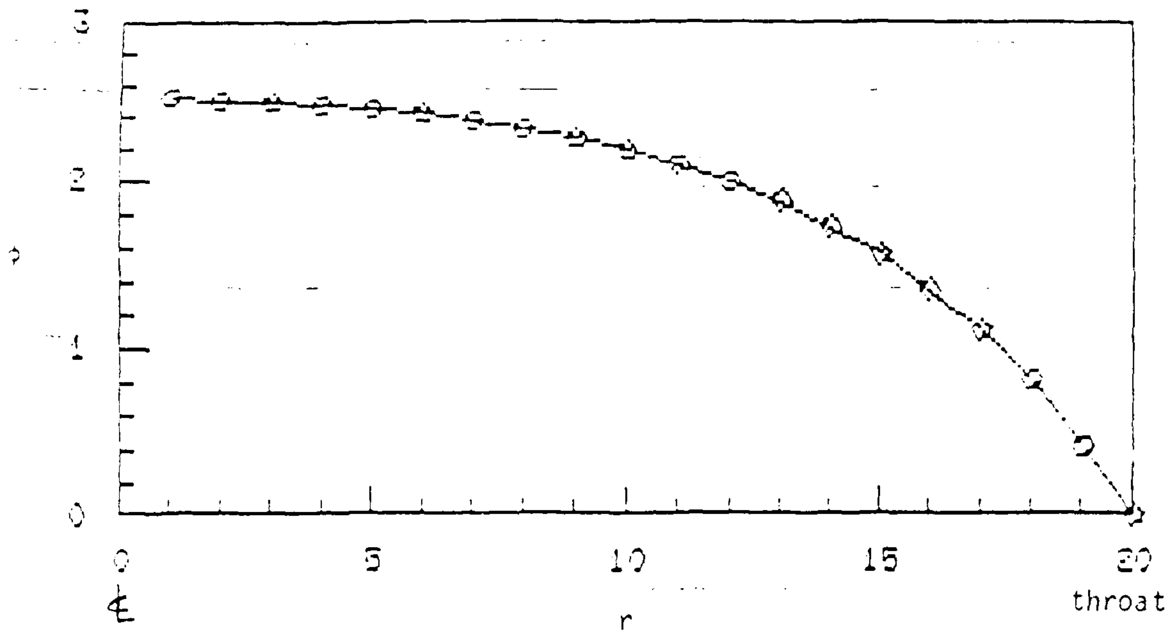
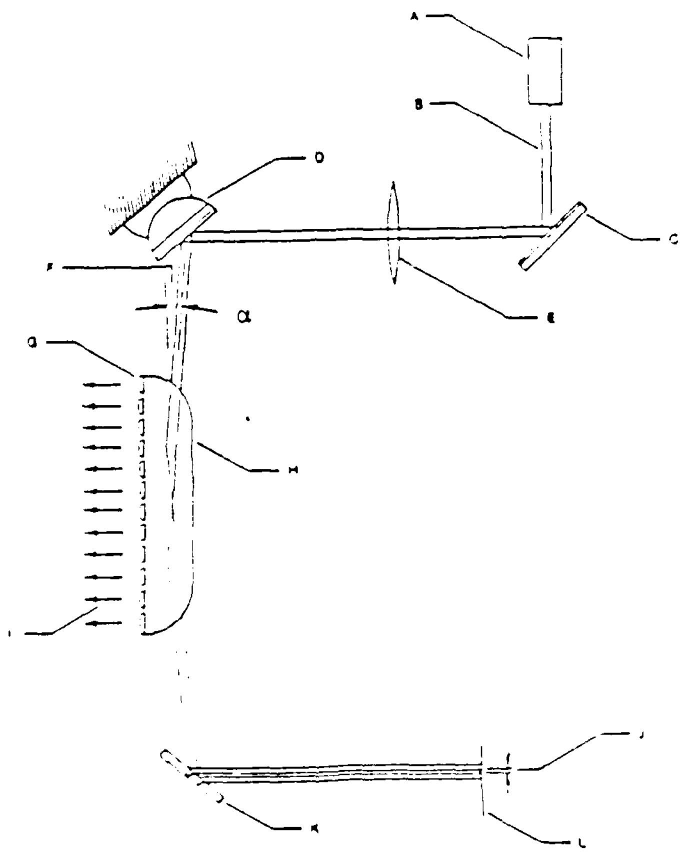
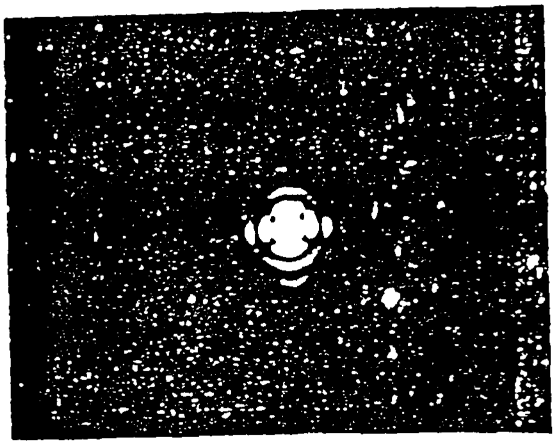


Fig. 3. Phase Distribution in an Axially Symmetric Nozzle Flow.



A. laser source
B. laser beam
C. primary surface reflector
D. translatable mirror
E. prefocussing lens
F. angle of incidence
G. porous membrane
H. density layer
I. flow field through porous surface
J. area where fringes appear
K. lateral shear plate
L. viewing screen

Fig. 4. Layout of Optical System for Gas Mirror.



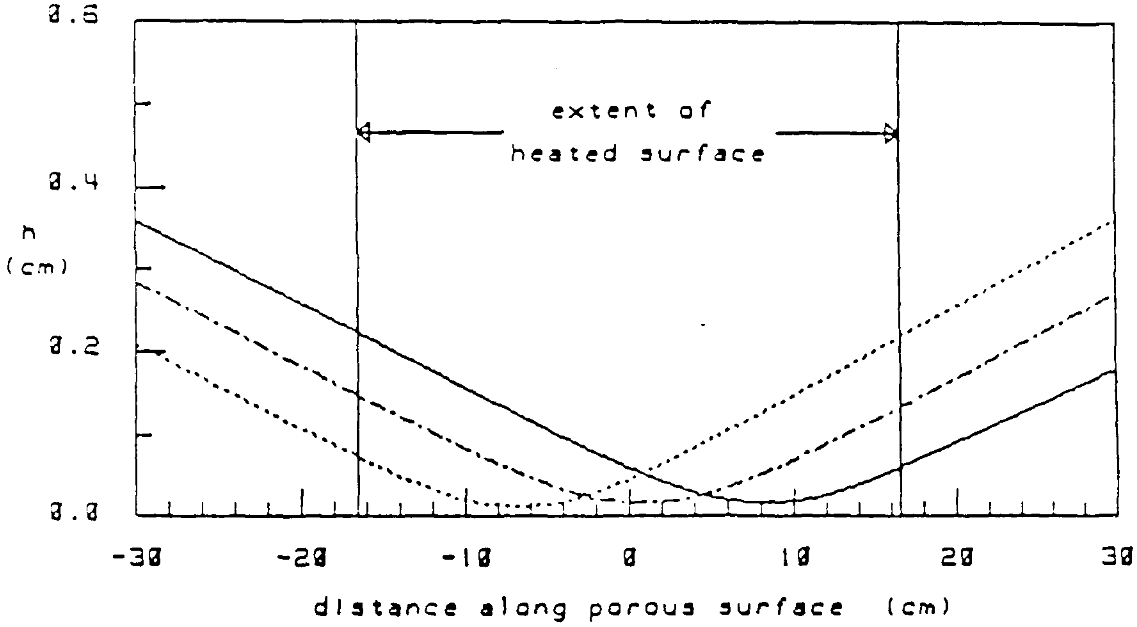


Fig. 5. Effect of Porosity Scale on Far Field Pattern of a Top Hat Beam. T_W = 420°K and α_i = -0.58°.

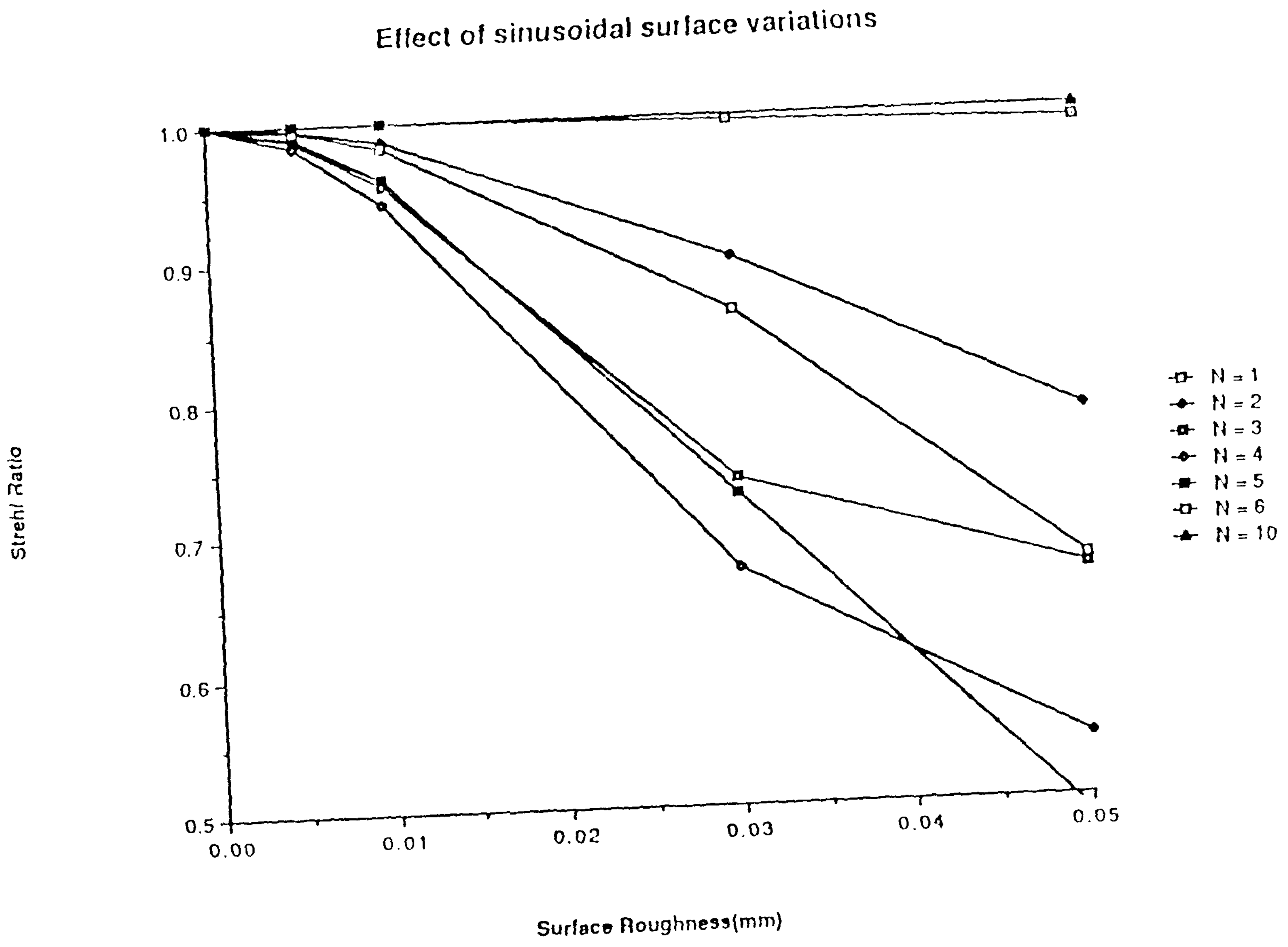


Fig. 6. Strehl Ratio vs. Surface Roughness

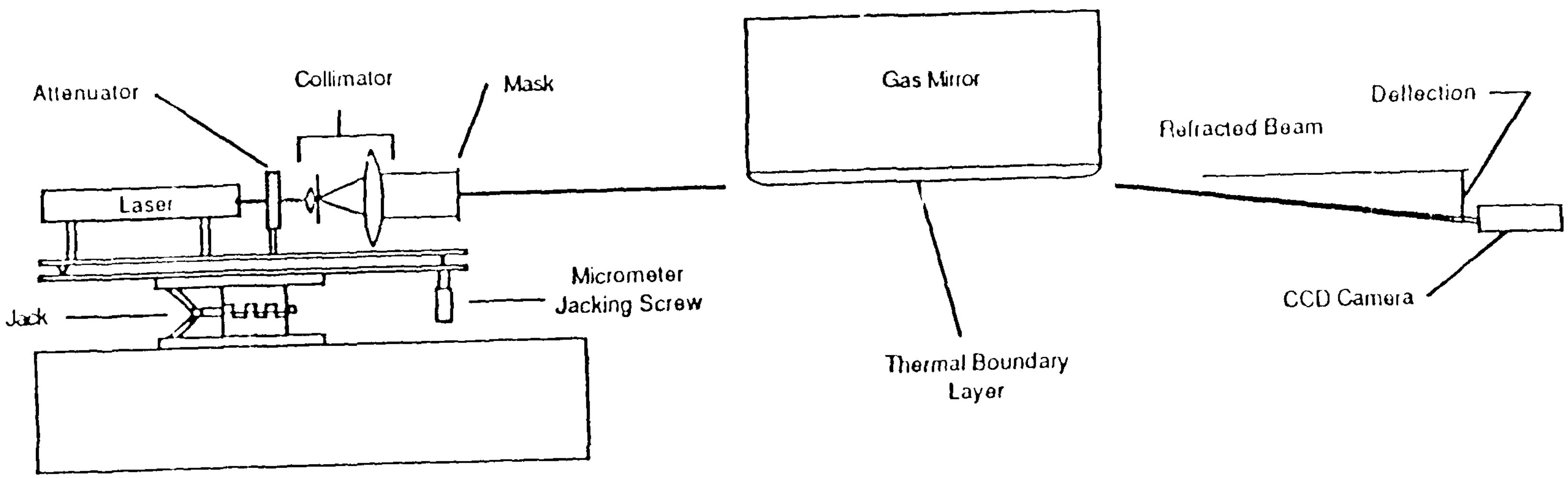


Fig. 7: Optical System for Strehl Ratio Measurement.

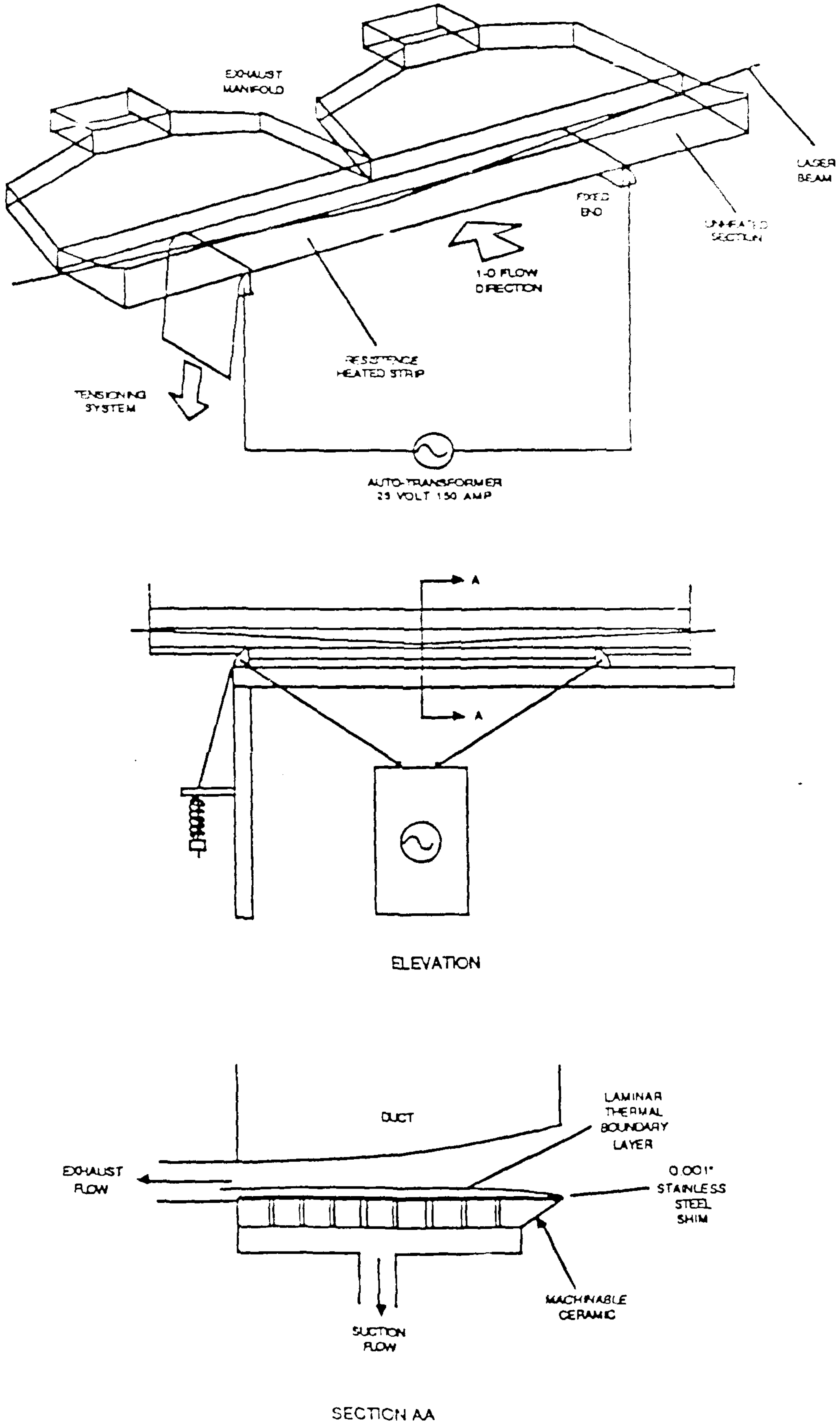


Fig. 8a: Schematic of new experimental apparatus.

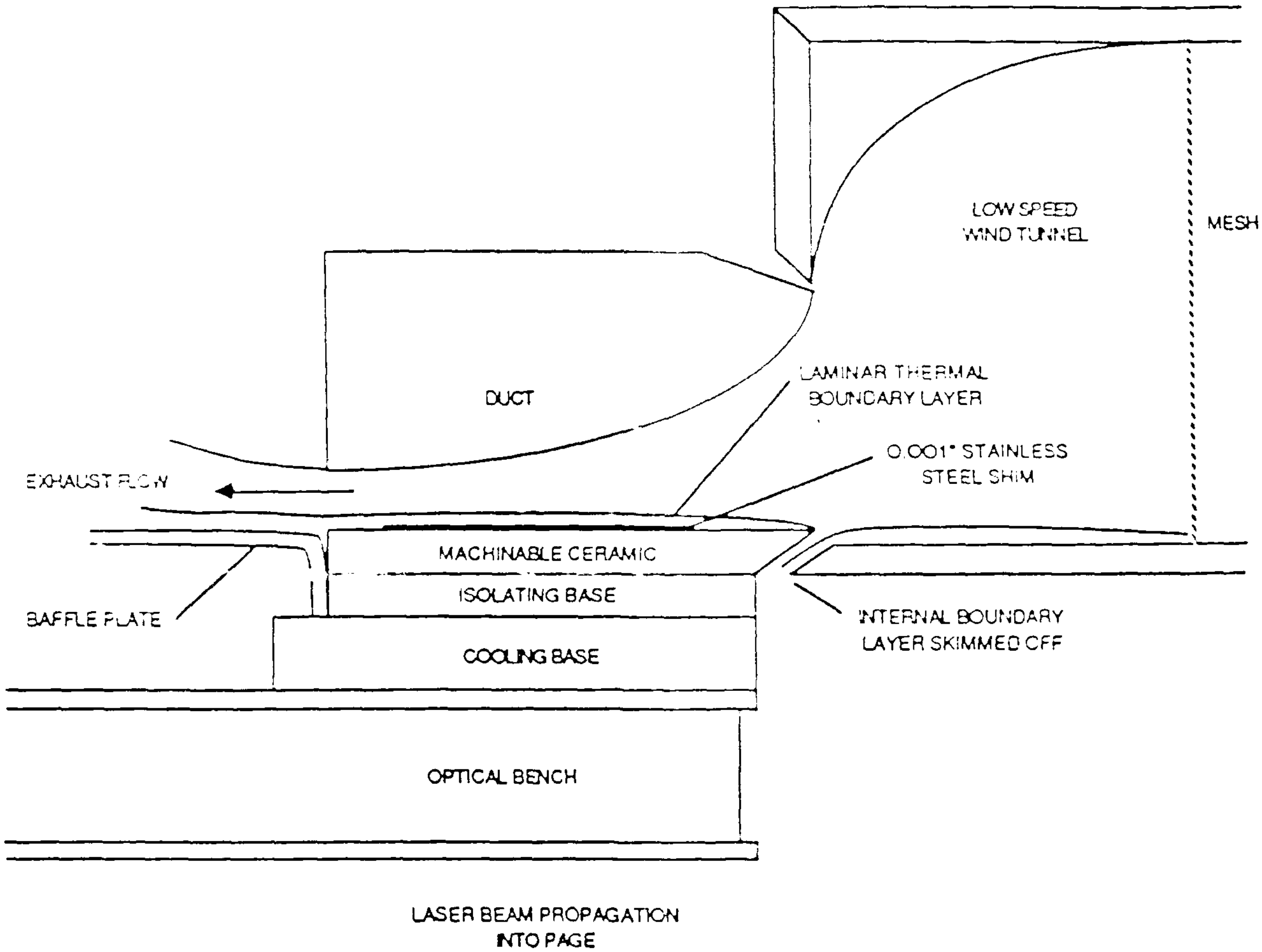


Fig. 8b: Enlargement of Wind Tunnel Cross Section

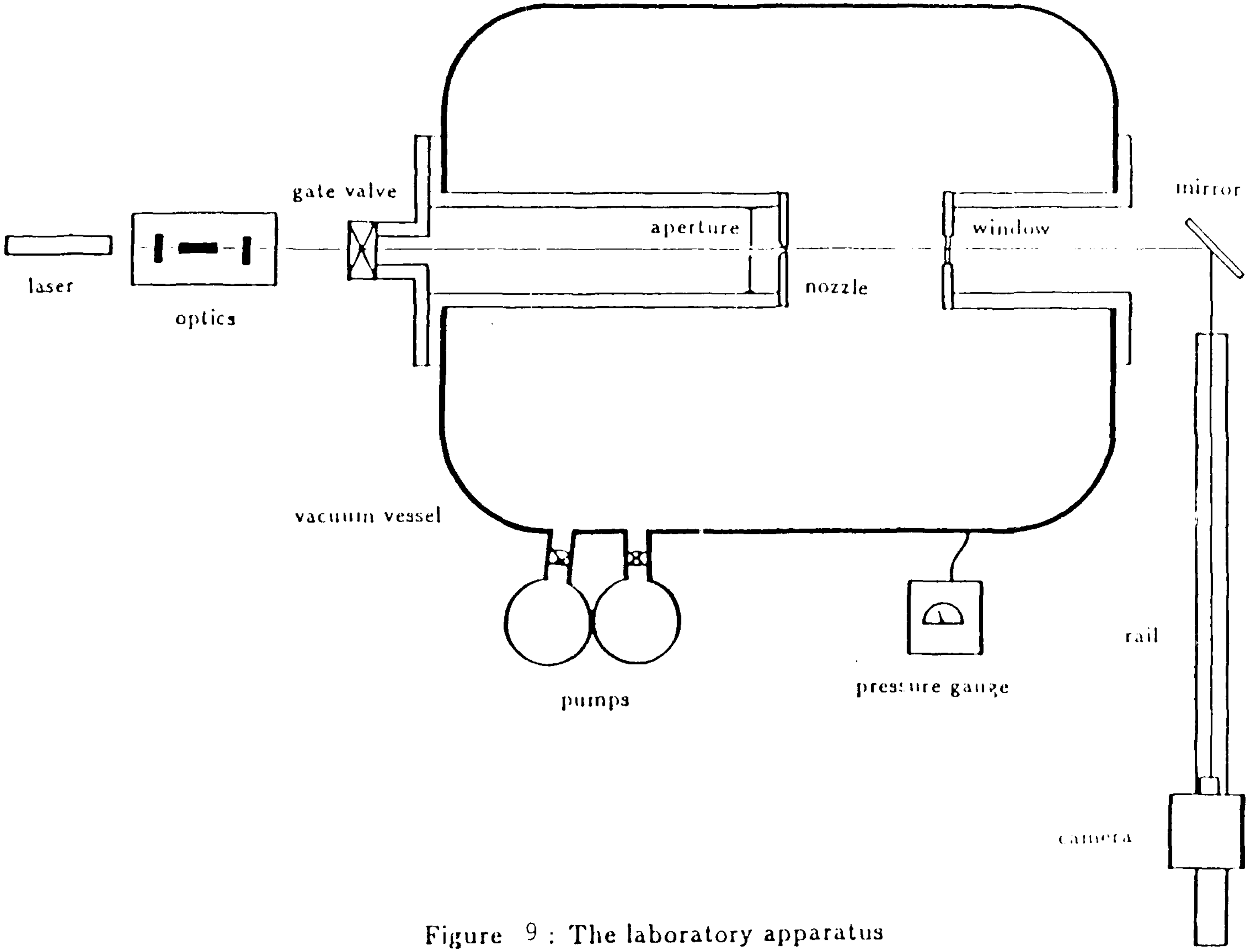


Figure 9 : The laboratory apparatus

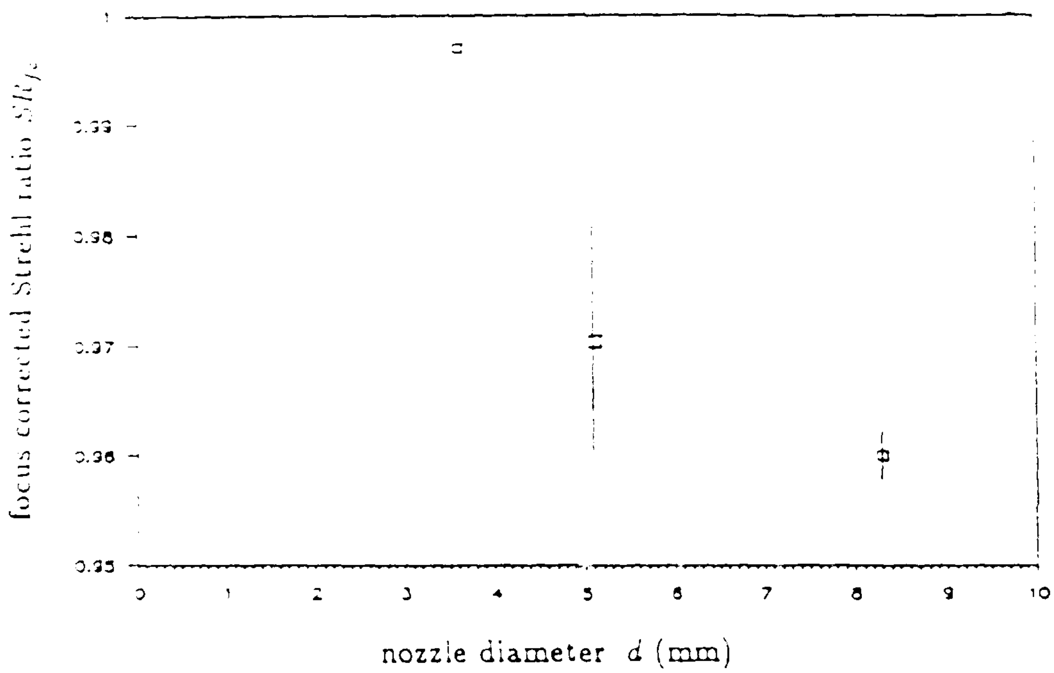


Figure 10 : Average focus corrected strehl ratios for the smooth nozzles. Bars indicate variation with aperture size.

APPENDIX A

Entry Flow Tubular Gas Lens

For the readers' convenience, the basis of the gas optics ideas are given here. A gas lens formed by subsonic flow through finite length pipe can be the basis of a lens. This lens is produced by a hot slow flow of gas, maybe Ar or a mixture of Ar and N_2, flowing through a cold pipe. The density distribution (index profile) of this case causes a coaxial light beam to diverge. The slow speed associated with this idea suggests that laminar Poiseuille or entry pipe flow can be achieved with nonsteady effects kept to a minimum. Figure A1 shows the lens schematically. If the flow speed is too small the gas uniformly cools with no resultant effect. Similarly, if the flow is too fast the gas does not cool and again there is no effect. There is a maximum effect in between. Using theoretical estimates a diverging beam of 1/100 radian can be produced with argon at 1 atm. These are quite minimal requirements and can easily be set up in the laboratory to test. Of course, flow entrance and exit conditions and temperature profiles in the pipe must be carefully controlled. A similar lens could also be constructed using diffusion of dissimilar gases rather than heat.

Glancing Gas Optics

A glancing incidence reflecting gas surface can be produced. This can be designed by using a porous wall also shown in Figure A1. Imagine a hot porous wall in contact with cold gas. The diffusion of heat produces a thermal boundary layer at the surface. This is stabilized by the suction at the

porous wall. The result is a thin adjustable layer having a refractive index profile. For small temperature changes one finds

$$\frac{T-T_c}{T_H-T_c} = e^{-\rho_0 V_0 y \frac{Pr}{\mu}} = e^{-y/\delta} \quad \text{and} \quad \rho = \frac{B}{T}$$

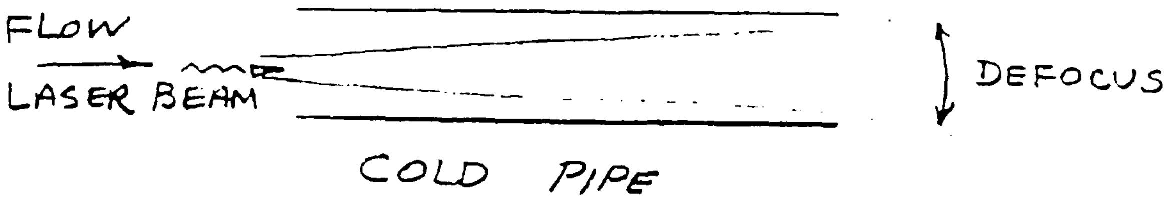
with a layer thickness, $\delta = Pr_\mu/\rho_0 V_0$, the thickness is controlled by adjusting the density or the velocity of the flow field. The easiest control is of course the suction velocity, V_0. Treating the layer as a discontinuity (only for approximation) we find $\Delta\theta \sim 1^\circ$ is possible for argon at 1 atm if $T_H-T_c = 300^\circ K$. It should be noted that the light beam is controlled by the shape of the porous surface much like a mirror. That is, if defocusing is wanted, then the surface is convex. It is also possible to defocus the beam by varying T_H on a flat surface. Under no circumstances is it necessary that the laser beam touch the porous surface for this reflection process. In fact, the porous material could be ceramic. An uncontrolled variation in porosity should be avoided as this would create a nonuniform thermal layer and a reduction in optical quality would be apparent.

Axial Subsonic-Flow Lens

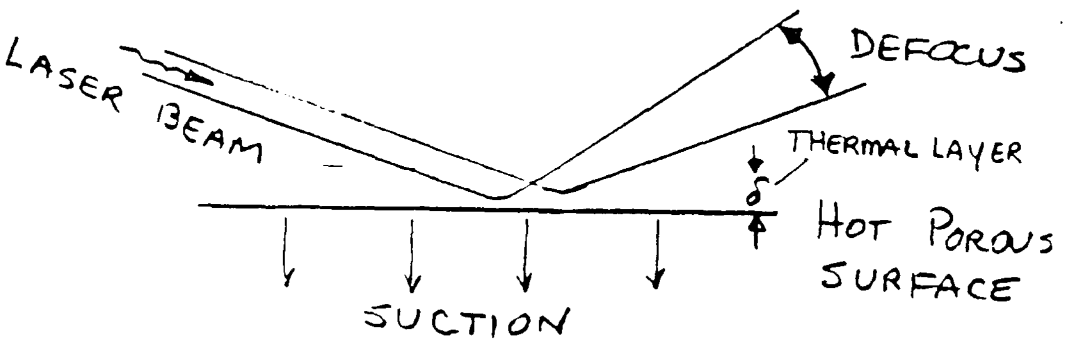
Another interesting lens possibility is to use the slightly compressible flow of a subsonic axially symmetric nozzle also shown in Fig. A1. In this case, the laser beam is to be oriented axially down the center line of the flow and the density field is expected to provide a defocusing action. The nozzle throat needs to be sized slightly larger than the laser beam diameter, probably on the order of one centimeter. Because subsonic flow is used, the core flow not involved with the nozzle boundary layer should be steady and provide a good gas lens. One advantage of this approach is the relatively

short duration exposure of gas to the high intensity laser beam. If defocusing action is apparent as we suspect, the strength and quality of the lens can be calculated. The lenses may also be arranged back to back, thus increasing the divergence angle of the beam with little effective loss through the flow field. The symmetric nature of this lens system may also produce a desirable two-dimensional laser beam expansion.

- Entry pipe flow (thermally induced defocus)



- Gas mirror (thermally induced defocus)



- DeLaval nozzle geometry (flow induced defocus)

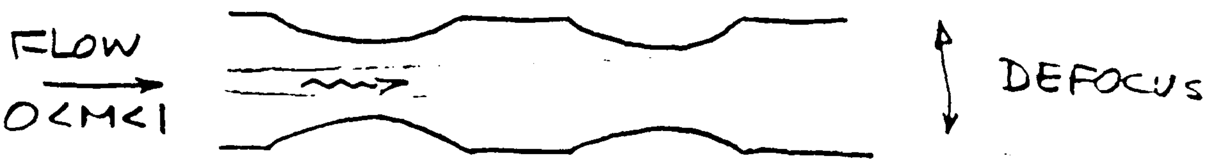


Fig. A1. Gas Optics Approaches.